Verifying Forecasts of Maximum Mixing Height for Greensboro, NC
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Introduction

The mixing height is defined as the height of the layer adjacent to the ground over which pollutants or any constituents emitted within this layer or entrained into it become vertically dispersed by convection or mechanical turbulence (P. Selbert et al. 2000). The National Weather Service (NWS) regularly produces forecasts of the mixing height to help users assess dispersion and anticipate air quality issues. Mixing height forecasts are provided to fire weather users through pre-suppression and gridded forecasts which are issued at least twice a day, and through spot forecasts which are issued as requested. Forecasts of mixing heights are also used to provide support for hazardous materials incidents.

Problem

The accuracy of mixing height forecasts is becoming more important to fire weather users and regulatory agencies given the growing public sensitivity to air quality issues. Despite the need, NWS mixing height forecasts are rarely verified, since the mixing height is not observed directly, and must be estimated or parameterized from vertical profile measurements.

Methods to Estimate the Maximum Mixing Height

There are several methods to determine the maximum mixing height, but they vary considerably, are subject to their own limitations, and are dependent on the availability and resolution of vertical profile data.

Holzworth Method

The Holzworth method (Holzworth, 1967) calculates the maximum mixing layer depth based on the afternoon surface temperature and the temperature sounding. This method lifts the surface parcel up the dry adiabat from the expected maximum temperature to its intersection with the temperature profile. The mixing height is then estimated as the equilibrium level of an air parcel with this temperature. It is dependent on the surface temperature and often the existence of a pronounced inversion at the top of the convective boundary layer.

Moisture Jump Method

The mixing height in the convective boundary layer can sometimes be identified as the height of a significant reduction in moisture, often accompanied by wind shear (Lyra et al., 1992). They described the mixing height for a convective profile as the height in which the mixing ratio decreased more than 0.01 g kg⁻¹ m⁻³.

Potential Temperature Method

This method first noted by Hegg (1989) analyzes the potential temperature or virtual potential temperature profile for the existence of a critical elevated inversion, which is assumed to indicate the top of the mixing height. The mixing height is at the lower range of a layer containing a positive potential temperature lapse rate and a significant temperature increase. This method appears to be the most scientifically rigorous and was used in this study.

Methodology

Forecasts of the daily maximum mixing height for Greensboro, North Carolina (KGSO) from 1 May 2009 through 30 April 2010 were subjectively verified. Vertical plots of virtual potential temperature, mixing ratio, Richardson number and wind direction/ speed were constructed from the 00 UTC and 12 UTC KGSO RAOB observations. The 00 UTC KGSO radiosonde observations were subjectively analyzed to determine the maximum mixing height during the previous convective day using the potential temperature method. Archived surface observations, local radar imagery, and satellite imagery were used to identify synoptic or mesoscale features that would have made the 00 UTC radiosonde unrepresentative. A total of 38 days (~10% of all forecast days) were removed from the data set because of missing observations or representativeness issues such as convection, frontal passages, or localized precipitation.

The maximum mixing height forecasts for the Guilford County, NC fire weather zone, which includes Greensboro (KGSO), were extracted from the Fire Weather pre-suppression Forecast (FWF) for each day of the study period. For each day, four forecasts are available, each from a different forecast cycle. A table was constructed containing the four forecasts available for a given day and the subjectively analyzed observed mixing height using the potential temperature method.

Results

- Observed mixing heights over the course of the year showed large day-to-day variability due to synoptic, diurnal, and mesoscale conditions.
- The average mixing height during the 327 days of available data was 3,566 feet, which is close to the average of 4,173 feet computed across 4 NWS sites by Garrett (1991).
- The average observed mixing heights during this one year period were greatest in April and smallest in December.
- The greatest observed mixing height was 9,600 feet on April 12th, with three other days experiencing mixing heights between 8,000 and 8,900 feet.
- For first period forecasts, the average first period mixing height error during the 327 study days, was 1,487 feet with a mean absolute error of 58%.
- A total of 12 days had errors in excess of 4,000 feet, 42 days had errors of more than 3,000 feet, and 102 days (nearly a third) had errors of 2,000 feet or more.
- For second period forecasts, 239 days out of 327 (73.1%) verified too high, while 80 days (26.9%) were too low.
- A total of 196 days (60% of all days) had observed mixing heights between 2,000 and 4,999 feet with only 70 days (21% of all days) had observed mixing heights of 5,000 feet or more.
- Forecasts were most consistent with the observed during the winter and early spring.

Applications and Lessons Learned

- Mixing height forecasts are consistently higher than the observed mixing height, with an average first period forecast error of 1,487 feet and a mean absolute error of 58%.
- The average observed mixing heights during this one year period were greatest in April and smallest in December.
- Forecasts that use the Holzworth method with a Skew T Log P diagram have a tendency to forecast mixing heights that are too high.
- Examining vertical profiles of potential temperature or virtual potential temperature with time along with wind speed/direction and mixing ratio is more scientifically rigorous than using the Holzworth technique alone.
- Forecasters should note that the mixing height is the height above ground level (AGL) and not mean sea level (MSL). Different sets of forecast guidance may use either AGL or MSL, and with KGSO located at 926 feet above MSL, this represents another potential source of error.
- Subjective assessment suggests that model guidance may be too high with the mixing height on many days, especially during fair weather and deep mixing days.
- The degree to which any method is successful depends on the availability and resolution of data (observations or model-generated). Even when data is available, the mixing height may contain complicated structures, which makes precise definition of the top of the layer difficult.

Acknowledgements

Whitney Rushing (NC State University) provided a great deal of assistance with data collection and organization. Rebecca Duell (NC State University) provided assistance with data manipulation and creating the various charts.

05 September 2009 Case Study

- Central North Carolina was on the western periphery of a ridge of high pressure that was located off the southeast U.S. coast and under the influence of weak surface high pressure. 
- Fair weather with clear skies resulted in a typical diurnal pattern of surface temperature and vertical mixing height evolution across the state.
- Given the above, a climatologically typical diurnal boundary layer evolution likely occurred. Thus it is appropriate to use the 00 UTC 06 September KGSO RAOB to determine the maximum mixing height for the 05 September convective day.

KGSO Maximum Mixing Height Forecasts and Observed for 05 September 2009

<table>
<thead>
<tr>
<th>Forecast Period</th>
<th>Forecast Issued</th>
<th>Forecast Valid</th>
<th>Forecast Height</th>
<th>MaxT</th>
<th>Average Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Period</td>
<td>00 UTC 05 Sep</td>
<td>00 UTC 06 Sep</td>
<td>6,900 feet</td>
<td>31.1°C</td>
<td>58%</td>
</tr>
<tr>
<td>2nd Period</td>
<td>00 UTC 05 Sep</td>
<td>00 UTC 06 Sep</td>
<td>6,400 feet</td>
<td>31.1°C</td>
<td>65%</td>
</tr>
<tr>
<td>3rd Period</td>
<td>00 UTC 05 Sep</td>
<td>00 UTC 06 Sep</td>
<td>7,800 feet</td>
<td>31.1°C</td>
<td>73%</td>
</tr>
<tr>
<td>4th Period</td>
<td>00 UTC 05 Sep</td>
<td>00 UTC 06 Sep</td>
<td>7,100 feet</td>
<td>31.1°C</td>
<td>80%</td>
</tr>
</tbody>
</table>

- Maximum observed mixing heights were greatest in April with 9,600 feet on April 12th. Three other days had mixing heights greater than 7,800 feet.
- For first period forecasts, 239 days out of 327 (73.1%) verified too high, while 80 days (26.9%) were too low.
- A total of 196 days (60% of all days) had observed mixing heights between 2,000 and 4,999 feet with only 70 days (21% of all days) had observed mixing heights of 5,000 feet or more.
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